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Aquifers of Nebraska II: The Niobrara Aquifer

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Conservation and Survey Division
School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska–Lincoln

Bulletin 9 (New Series)

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ABSTRACT

The marine shale, chalk, marl, and chalky limestone of the Niobrara Formation directly underlie Quaternary sediments in 23 counties from south-central to northeastern Nebraska. Nevertheless, the formation serves as an aquifer only in and around Cedar, Madison, and Nuckolls counties. Niobrara aquifer wells mostly supply irrigation, domestic, and livestock needs. Two hundred of the approximately 230 active registered wells in Nebraska that are screened entirely in the Niobrara aquifer are in Cedar County and environs. About another 200 wells in this area are screened in both the Niobrara aquifer and overlying Quaternary sediments. Wells screened entirely in the Niobrara aquifer in Cedar County range in total depth from about 50 to 220 ft (15 to 67 m) in both confined and unconfined hydraulic conditions. One-fifth of these wells yield 500 gpm (1,900 lpm) or more. Groundwater in the aquifer generally flows north-northeast through Cedar County toward the Missouri River.

Approximately 15 registered active wells in the Niobrara aquifer lie in the vicinity of Norfolk in Madison County. These chiefly domestic wells yield 20 gpm (76 lpm) on average and are located atop a bedrock high under the Elkhorn River and its North Fork. The static water level in these wells is at or above the top of the formation. An additional ten wells are partially screened in the Niobrara aquifer in this area.

In and around Nuckolls County, 16 wells are screened entirely in the Niobrara aquifer, mostly located on the divide between the Little Blue and Republican rivers. These wells supply domestic and livestock needs, yield about 10 gpm (38 lpm) on average, and indicate a mix of confined and unconfined hydraulic conditions. An additional 110 wells in this area are partially screened in the Niobrara aquifer. Documenting the present state of geological knowledge, areal extent, and hydrogeologic properties of the Niobrara aquifer will facilitate focused data collection and sustainable management in the future.

INTRODUCTION

Purpose and Scope

The purpose of this publication is to characterize the Niobrara Formation in eastern Nebraska, where it is a secondary groundwater aquifer in places. The following analyses of the quantity, quality, and movement of water in the aquifer provide additional information for effective resource management and contribute to the informed decisions of well owners, drillers, and water resources professionals. From a purely geological standpoint, this bulletin provides new information about the formation between well-studied outcrop areas in northeastern Nebraska and western Kansas. A summary of the geological history and depositional environment of the Niobrara Formation provides the reader with a regional context to better understand the properties of this aquifer.

Methods

Interpretations in this study were drawn from examination of 7,300 geologic logs from registered water wells (Nebraska Department of Natural Resources, undated). Registered well logs present interpretational challenges because variations in drilling methods, drilling fluid programs, and operator experience can make a substantial difference in the *in-situ* interpretation of lithology. Therefore, as a form of quality control, these logs were compared to the detailed logs of a much smaller number of Conservation and Survey Division (CSD) stratigraphic test holes drilled by CSD geologists (Conservation and Survey Division, undated).

Although the variability of such geologic data impart uncertainty to mapping, coherent patterns emerged in the course of this study. Maps estimating the configuration of the top of the Niobrara Formation and the horizontal hydraulic gradient within the aquifer are examples of interpreted patterns, and are presented here. Geologic and hydrogeologic contour maps were made using ESRI's geostatistical analysis ordinary kriging interpolation method (ESRI® ArcGIS 10.2). Interpolation is a process that estimates values (e.g., the elevation of the top of the Niobrara Formation) between actual data points. Kriging is a specific kind of interpolation method that assigns weights to values at existing data points based on a pattern of spatial continuity, as determined by a semivariogram (a mathematical function that relates difference in value to distance between points), and then estimates a best-fit surface (e.g., the top of the Niobrara Formation). The surface estimated by kriging does not necessarily pass through the data points, and because the method seeks to best fit intermediate values, the extreme values of the data set may not be represented in the best-fit surface (Paciorek, 2008).

Geologic and Geographic Setting

The marine shale, chalk, marl, and chalky limestone of the Niobrara Formation serve as both a petroleum reservoir and as a groundwater aquifer in the interior of North America. Numerous studies of the stratigraphy, petrography, and economic potential of the Niobrara Formation have been carried out in Kansas, Colorado, Wyoming, North Dakota, and South Dakota (e.g. Bolin, 1952; Scholle, 1977a; Hattin, 1982; Shurr and Rice, 1987; Longman et al., 1998). The Niobrara Formation has long been recognized as an aquifer in Kansas (Macfarlane, 2000), but the present report is the first to comprehensively assess it as an aquifer in Nebraska.

The geography of the study area (Fig. 1) includes gently rolling to flat landscapes of four Major Land Resource Areas: (1) Loess Uplands north of the Platte River; (2) Central Nebraska Loess Hills near the Platte River; (3) Central Loess Plains south of the Platte River; and (4) Rolling Plains and Breaks in the Republican River valley (U.S. Department of Agriculture, 2006). The loamy to sandy soils in the study area are developed on Quaternary loesses, alluvium, and eolian sand (U.S. Department of Agriculture, 2015). Cultivated crops are the dominant land use, although herbaceous cover is common (U.S. Geological Survey, 2011). Average annual precipitation is about 28 in (710 mm) across most of the study area, but it decreases southwestward to 22 in (560 mm) in Red Willow County (U.S. Department of Agriculture, 2012).

The Niobrara Formation is the first bedrock unit encountered by drillers in all or parts of 23 counties. This subcrop and outcrop belt extends northeast to southwest across eastern Nebraska and ranges from approximately 2 mi (3 km) to 60 mi (97 km) in width (Fig. 2). The Niobrara Formation serves as an aquifer only in and around Cedar, Madison, and Nuckolls counties. The Niobrara aquifer is the sole source of water to about 230 wells, and a partial source of water to an additional 320 wells.

Niobrara Formation outcrop on south side of Republican River near Bloomington, in Franklin County, Nebraska. Vehicle at lower left is 5.5 ft (1.7 m) in height.

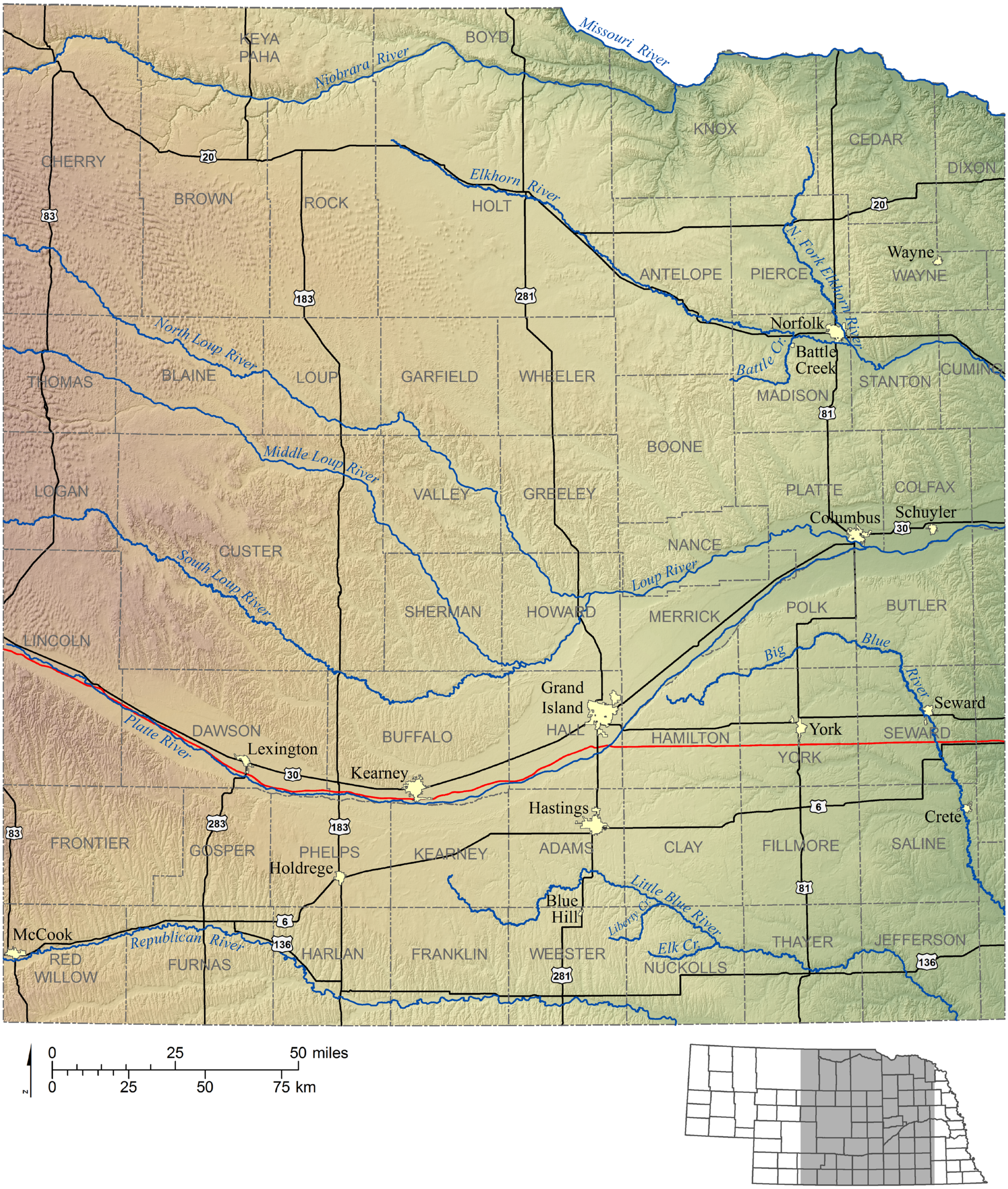


Figure 1. Study area and environs (gray on the index map, lower right).

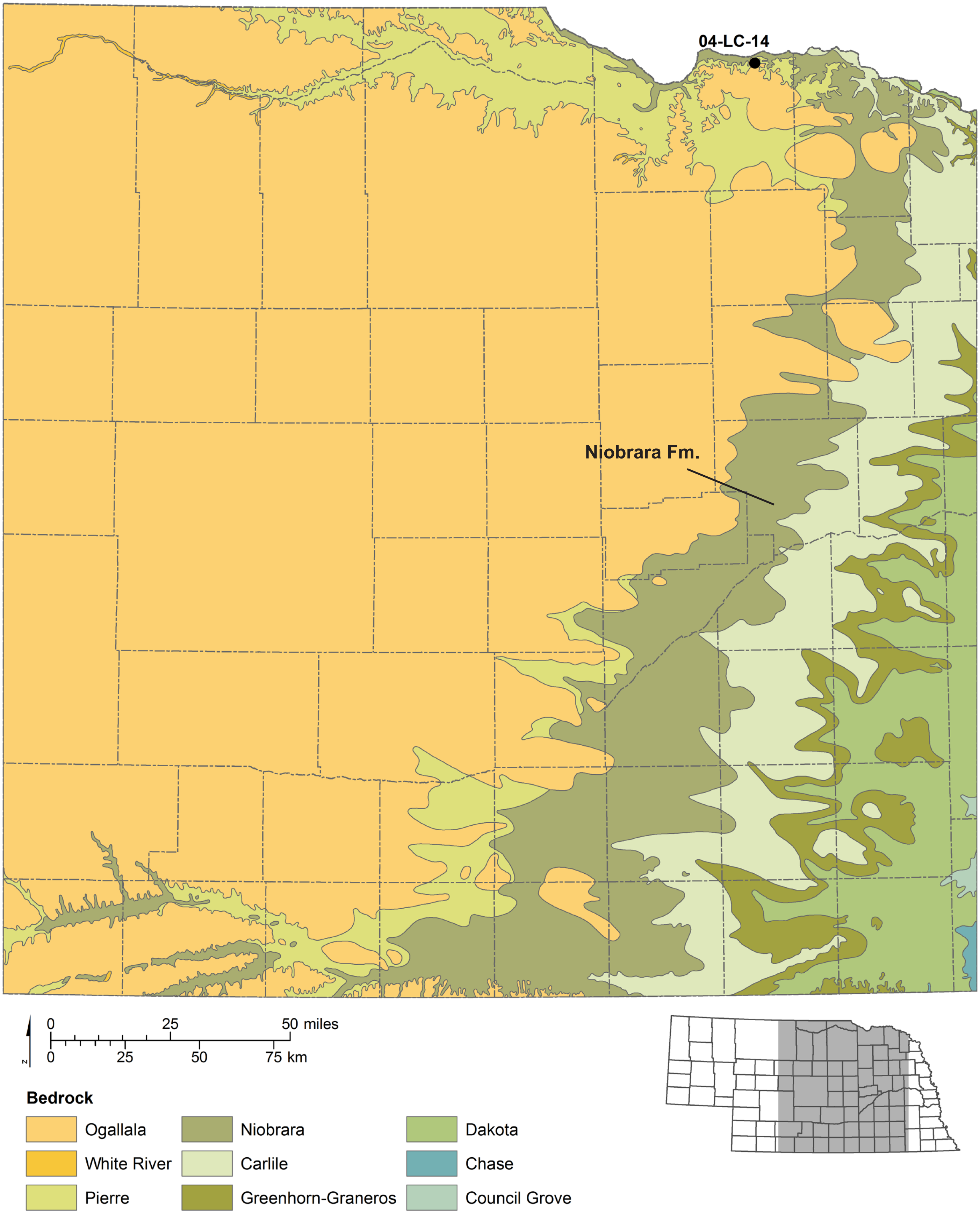


Figure 2. Bedrock geology (Burchett, 1986) of the study area and environs (gray on the index map, lower right).

GEOLOGY OF THE NIOBRARA FORMATION IN NEBRASKA

History and Depositional Environments

The Niobrara Formation (Turonian-Campanian) was named by Meek and Hayden (1862) from exposures along the Niobrara River near its confluence with the Missouri River in Knox County, Nebraska. It is part of a regionally consistent succession of Cretaceous strata in the former Western Interior Seaway (WIS) (Fig. 3), that can be correlated from New Mexico to southern Saskatchewan (Baltz, 1965; Shurr and Rice, 1987; Yurkowski et al. 2006; Merewether et al., 2007).

The Western Interior basin, in which the Niobrara Formation was deposited, was an asymmetrical basin with a narrow shelf on its western side adjacent to the Cordilleran Orogen. Immediately eastward, there was a sharp drop off into the deepest part of the basin, which probably had a maximum water depth of about 600 to 900 ft (183 m to 274 m) (Miall et al., 2008). Subsidence in the basin was caused by crustal loading of the Cordilleran fold-thrust belt, subduction of the oceanic crust of the Farallon Plate, and mantle flow (e.g. Flament et al., 2013; Heller and Liu, 2016). Sea levels in the basin also fluctuated over time (e.g. Miller et al., 2005). Abundant terrigenous sediment from highlands uplifted in the Early Cretaceous by the Sevier Orogeny (e.g. Armstrong, 1968; Kauffman, 1977), gradually filled the basin from the west. The Western Interior basin gradually shallowed eastward across present Nebraska; the eastern side of the sea was bordered by more geologically stable lowlands that contributed less terrigenous sediment (Kauffman, 1977; Witzke et al., 1983). As deposition in the basin continued through the late Cretaceous, marine sediments were deposited farther and farther eastward into present Minnesota and Iowa (e.g. Hattin, 1975; Witzke et al., 1983). The basin began to break up in the late Cretaceous (Campanian-Maastrichtian) due shallow subduction of the Farallon Plate associated with the Laramide Orogeny (Miall, 2008).

Cenozoic erosion probably removed the Niobrara Formation and its stratigraphic equivalents over large parts of the formerly eastern side of the Western Interior basin, including southeastern Nebraska, eastern Kansas, and much of Iowa and Minnesota, although the formation remains in northwestern Iowa and southwestern Minnesota (Scholle, 1977a; Witzke et al., 1983; Merewether, 1983; Cobban et al., 1994). The crest of the Sioux Quartzite Ridge in southeastern South Dakota likely remained emergent during maximum sea level and the deposition of the Niobrara Formation. Nevertheless, the Niobrara Formation and a possible local equivalent, the Split Rock Creek Formation, have been documented on the flanks of the ridge (Shurr, 1981; Ludvigson et al., 1981).

Multiple advances of the Laurentide Ice Sheet during pre-Illinoian times, between 2.5 million and 640,000 years ago, significantly altered Cretaceous and Cenozoic rocks in the northeastern portion of the study area (Todd, 1914; Simpson, 1960; Reed and Dreeszen, 1965; Hedges, 1975; Boellstroff, 1978a; 1978b; Roy et al, 2004; Balco et al., 2005; Rovey and Bettis, 2014). The present Missouri River trench, at the northern border of the study area, formed only after the final retreat of the ice sheet from Nebraska.

Lithology

Marine shale, chalk, marl, and chalky limestone facies with thin beds of bentonite are present in the Niobrara Formation in North Dakota, South Dakota, Nebraska, Kansas, Colorado, and Wyoming (Kauffman, 1977; Shurr and Rice, 1987; Hattin, 1982; Witzke et al., 1983; Diffendal and Voorhies, 1994; Longman et al., 1998). The term "marl" was used in some early literature to describe the Niobrara Formation (e.g. Darton, 1905), but the older usage of that term encompassed a variety of different lithologies consisting of mixtures of carbonate, clay, silt, and/or sand. "Marl" is usually applied more strictly today to carbonate lithology that contains 35-65% clay (e.g. Longman et al., 1998). For the purposes of the present study, however, the term is used to describe a mix of carbonate and clay particles with no specific percentages implied.

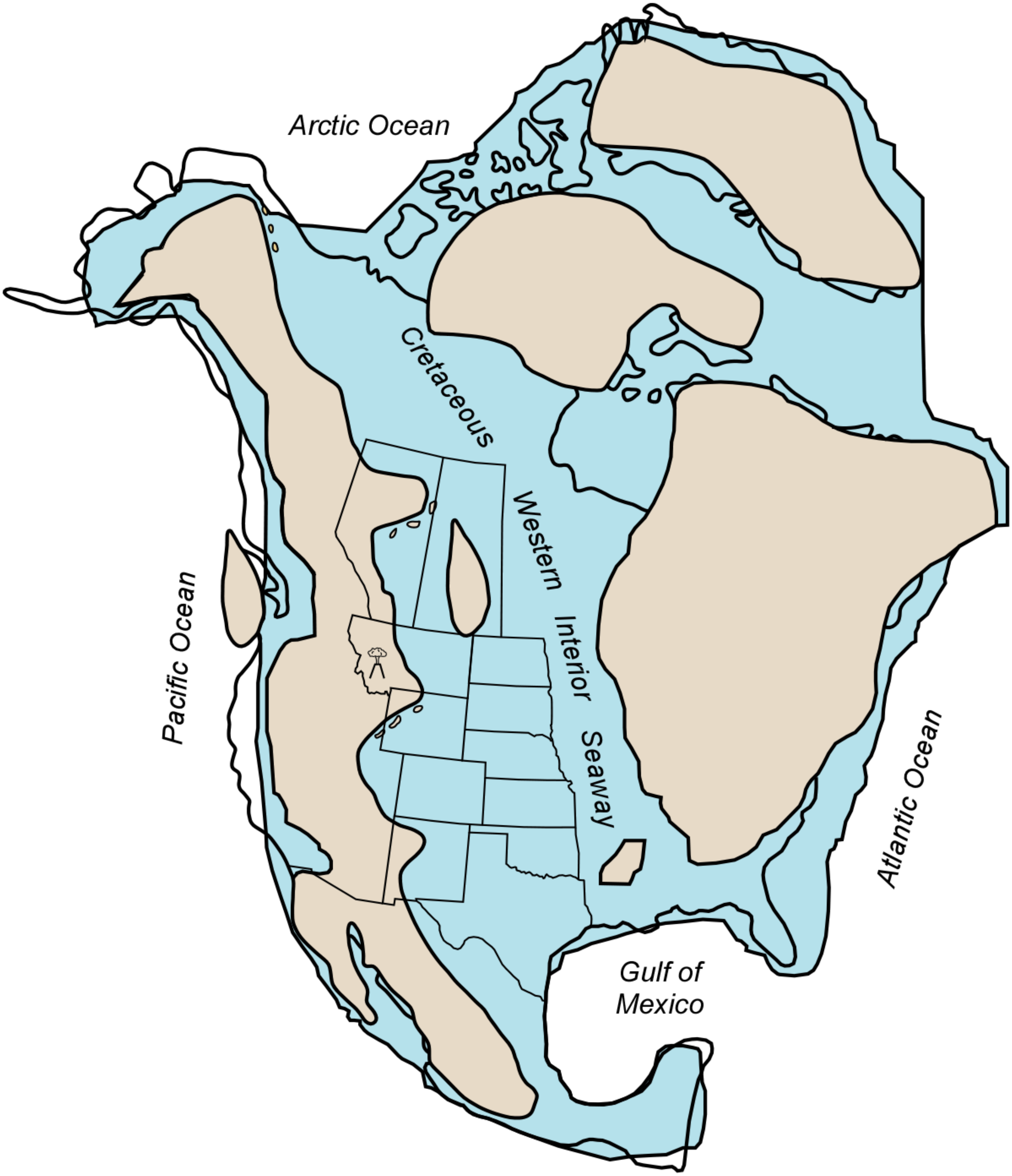


Figure 3. Estimated position of Western Interior Seaway shorelines during the deposition of the Niobrara Formation. Used with permission from R.F. Diffendal, Jr., 2017.

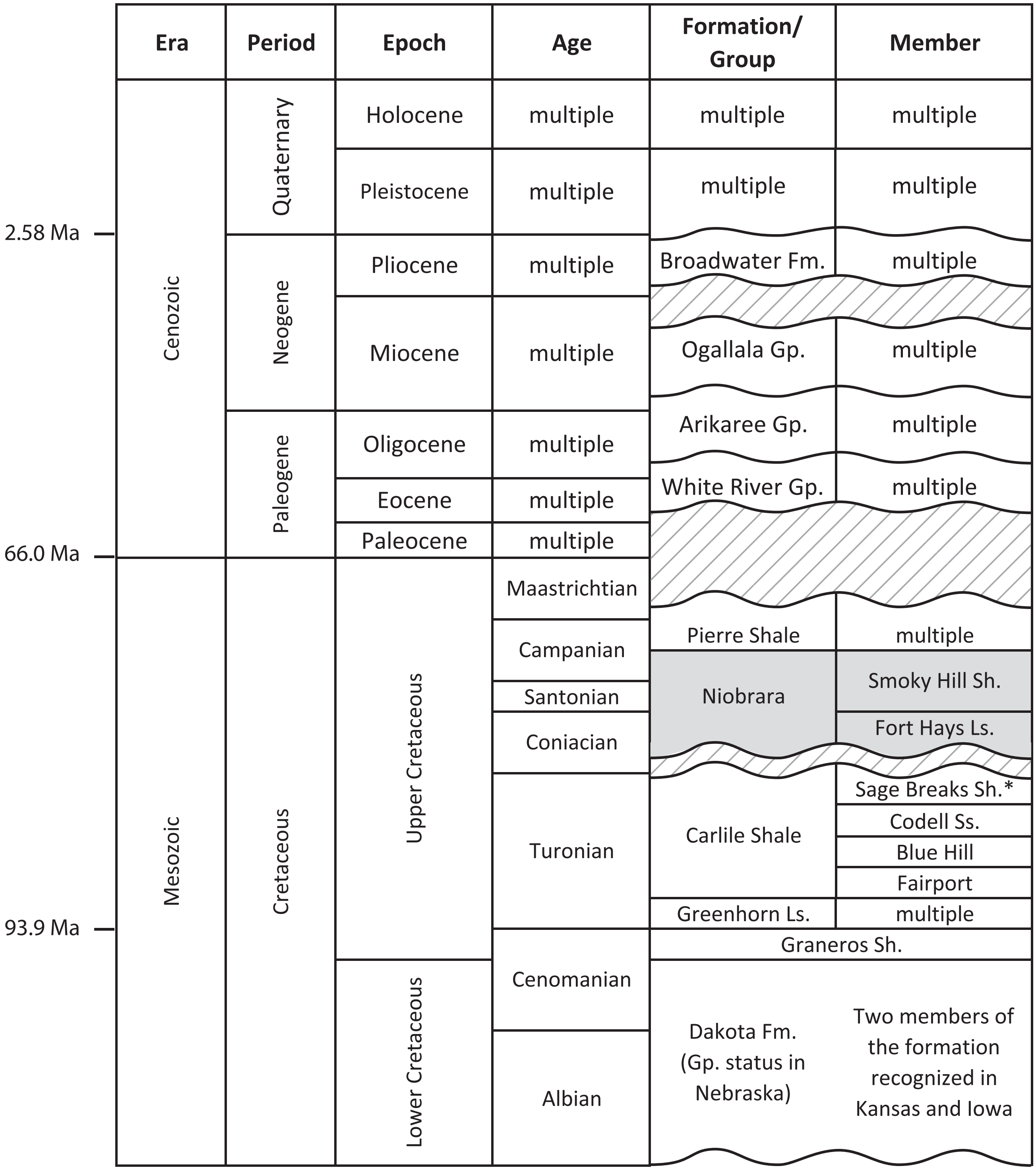
The difference between chalk and limestone is also sometimes unclear, but it is important to note that while both rock types consist mostly of calcium carbonate, chalks are relatively homogeneous, biogenic, stable low-magnesium calcite. Limestone, however, contains various amounts of magnesium, and both aragonite and calcite crystal structures (e.g. Scholle, 1977b). The precursor sediments of chalks consisted of the remains of two types of planktonic, photosynthesizing micro-organisms: coccolithophores (Phylum Haptophyta, Class Prymnesiophyceae) and foraminifera (Phylum Retaria, Subphylum Foraminifera). Coccoliths, the minute "scales" that covered coccolithophores in life, are the primary constituent of Cretaceous chalks in the Western Interior basin. Coccolith-rich fecal pellets, probably formed by pelagic crustaceans, impart a distinctive speckled appearance to parts of the Niobrara Formation (Hattin, 1975; Longman et al., 1998; Yurkowski et al., 2006). Foraminifera are secondary components, and fragments of oyster and inoceramid clam shells are minor components (e.g. Bolin, 1952; Hattin, 1982; Scholle, 1977a). The chalks, limestones, and shales of the Niobrara Formation tend to be dark gray when fresh, but the chalks and limestones weather to light gray, light brown, or yellow (Hattin, 1982; Scholle, 1977a).

Thin bentonites (11.3 cm or less in thickness) in the Niobrara Formation are altered ashes from volcanoes west of the Western Interior basin (Bertog, 2013). Bentonites usually appear as soft, white, strata within outcrops; because of near-surface weathering, some bentonites appear as concentrations of iron oxide and gypsum (Hattin, 1982).

Stratigraphy

The Cretaceous succession in eastern Nebraska is the stratigraphic interval from the base of the Dakota Formation ("Dakota Group" of Condra and Reed, 1959) to the top of the Pierre Shale (Fig. 4), although in extreme western Nebraska the Fox Hills Formation (Upper Cretaceous) overlies the Pierre Shale (Condra and Reed, 1959). The contact between the Carlile Shale and the overlying Niobrara Formation is unconformable due to both erosion and nondeposition (Hattin, 1975), which lasted for about four million years in Nebraska (DeGraw, 1975; Merewether et al., 2007). After deposition of the Niobrara Formation, the sea shallowed again and produced an unconformity representing a hiatus of as much as six million years (DeGraw, 1975). Global sea level began to rise again at approximately 80 million years ago, prompting the deposition of the Pierre Shale during the transgressive phase of the Clagget Cyclothem (Witzke et al., 1983). Global sea-level fluctuations during the Late Cretaceous are now thought by some authors to have resulted from variations in the moderate volume of glacial ice on ancient Antarctica (Miller et al., 2003; Miller et al., 2005, Kominz et al., 2008), although displacement of water from ocean basins by young oceanic crust and fast sea-floor spreading (e.g., Seton et al., 2009) is the more traditional explanation of widespread mid- and Late Cretaceous epicontinental seas. Tectonic activity in surrounding areas caused post-depositional deformation, uplift, and erosion of Cretaceous sediments in eastern Nebraska, including the Niobrara Formation (Bunker, 1981; Witzke et al., 1983; Shurr and Rice, 1987).

The Niobrara Formation has been separated into two members across much of the Western Interior basin: The Fort Hays Limestone and the overlying Smoky Hill member, both of which were named for locations in Kansas (Williston, 1893; Cragin, 1896). The lower Fort Hays Limestone is mostly chalk and chalky limestone that was deposited during the transgressive phase of the Niobrara Cyclothem (e.g. Kauffman, 1977). It contains some of the purest chalk in the Western Interior and is 55 to 75 ft (17 to 23 m) thick in Kansas (Hattin, 1977). The carbonate content of the formation decreases considerably north and west of the Hartville uplift in the southeastern corner of Wyoming, which acted as a barrier to the warm southern currents in the Western Interior seaway, thereby limiting coccolith production and accumulation (Longman et al., 1998). The overlying Smoky Hill Member is mostly marl along the eastern margin of the seaway and alternating chalk, chalky shale, and marl units in the Denver basin (e.g. Hattin, 1977; Longman et al., 1998; Michaels, 2014). The alternating units appear to be rhythmic, and recent work suggests that increased siliciclastic-sediment input to the marls was caused by climate variations related



Era	Period	Epoch	Age	Formation/ Group	Member
Cenozoic	Quaternary	Holocene	multiple	multiple	multiple
		Pleistocene	multiple	multiple	multiple
	Neogene	Pliocene	multiple	Broadwater Fm.	multiple
		Miocene	multiple	Ogallala Gp.	multiple
	Paleogene	Oligocene	multiple	Arikaree Gp.	multiple
		Eocene	multiple	White River Gp.	multiple
		Paleocene	multiple		
Mesozoic	Cretaceous	Upper Cretaceous	Maastrichtian		
			Campanian	Pierre Shale	multiple
			Santonian	Niobrara	Smoky Hill Sh.
			Coniacian		Fort Hays Ls.
			Turonian	Carlile Shale	Sage Breaks Sh.*
					Codell Ss.
					Blue Hill
					Fairport
				Greenhorn Ls.	multiple
			Cenomanian	Graneros Sh.	
		Lower Cretaceous		Dakota Fm. (Gp. status in Nebraska)	Two members of the formation recognized in Kansas and Iowa
			Albian		

* applies in the vicinity of the Denver-Julesburg Basin

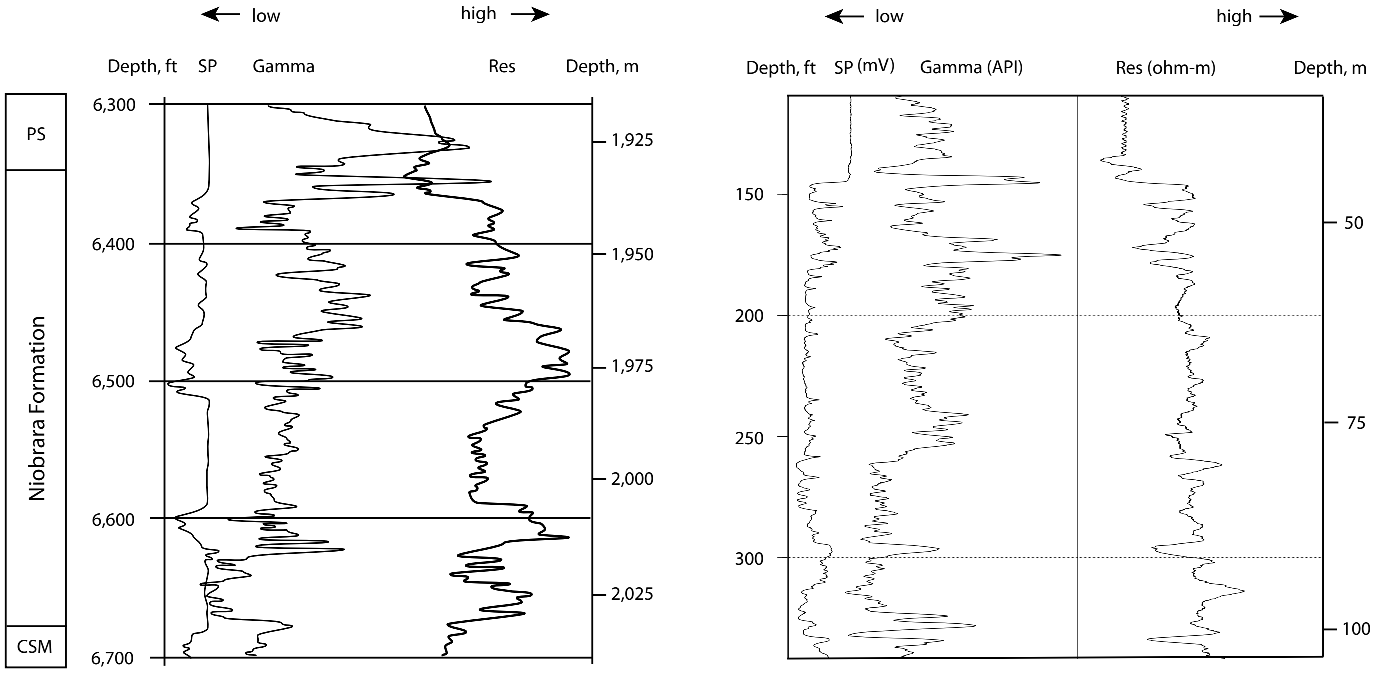
Ls = Limestone
Sh = Shale
Ss = Sandstone
Gp = Group
Fm = Formation
Ma = Million years ago

Figure 4. Stratigraphic chart with the Niobrara Formation and its members shaded. Undulating lines represent unconformities.

to Earth's orbital cycles (Locklair and Sageman, 2008). The Smoky Hill Member is 560 to 620 ft (170 to 189 m) thick in Kansas (Hattin, 1977).

Chalk, chalky limestone and marl lithofacies are also present in eastern Nebraska (e.g. Watkins and Diffendal, 1997; Diffendal et al., 2002), although a distinctive silty, sandy carbonate facies exists in Cedar County (Condra, 1908; Witzke et al., 1983). The Fort Hays Limestone is well exposed in some places in northeastern Nebraska, perhaps most notably along the southern bank of the Missouri River near the mouth of Bow Creek in Cedar County (e.g. Joeckel et al., 2011; Hattin, 1975). However, in other locations, even in Cedar County, it can be difficult to identify the contact between the two members in poorer exposures and, especially in bore holes (e.g. Bolin, 1952). The Mobridge Member of the Pierre Shale is a chalky unit that overlies Niobrara Formation in places (Watkins and Diffendal, 1997), which further complicates field identification of the members of the Niobrara Formation in Nebraska.

Data from a Conservation and Survey Division test hole drilled in northeastern Knox County in 2014 (04-LC-14, Fig. 2) show that the Niobrara Formation in that area is at least 185 ft (56 m) thick. The lithologic variability in the Niobrara Formation is evidenced by the changes in all of the curves on a geophysical log from this test hole and an electric log from the Denver-Julesburg Basin (Fig. 5) relative to the underlying Carlile Shale and the overlying Pierre Shale. The Niobrara Formation members were not formally defined in either hole, but the sharp excursion to the left on the 04-LC-14 gamma log at about 250 ft (76 m) coincides with the appearance of white limestone fragments, which are indicative of the Fort Hays Limestone. This interval also has slightly higher resistivity values relative to the material above, which is logged as dark gray marl and probably corresponds to the Smoky Hill Member. The sharp excursions to the right on the gamma log probably correspond to bentonite layers.



A. Partial log from API 26007219600000

B. Partial log from CSD testhole 04-LC-14.
VE ~ 2X relative to log A.

Figure 5. Geophysical well logs showing the Niobrara Formation. Log A depicts the Niobrara Formation in the Denver-Julesburg basin in Banner County near the Nebraska-Wyoming state line. Log B depicts the Niobrara Formation in Knox County. PS denotes the Pierre Shale, and CSM denotes the Codell Sandstone Member of the Carlile Shale.

Structural Geology

Upper Cretaceous strata throughout the Western Interior, including those of the Niobrara Formation, have been gently deformed (e.g. Bunker, 1981; Divine et al., 2016). Numerous faults have been observed in the Niobrara Formation and the overlying Pierre Shale in Harlan County (e.g. Miller and Steeples, 1996; Diffendal et al., 2002; Maher, 2014). There is evidence that the faulting in Harlan County may be the result of either the reactivation of basement structures (Miller and Steeples, 1996; Diffendal et al., 2002) or of diagenetically driven volume shrinkage associated with compaction and fluid expulsion (Maher, 2014).

The overall tectonic setting of the Midcontinent is compressive because the westward movement of North America creates ridge push and asthenospheric drag, which occurs most where the base of the lithosphere extends into viscous mantle material (e.g. Zoback and Zoback, 1980). Mantle flow probably also causes hydrodynamic stresses that result in crustal deflections (Flament et al., 2013; Heller and Liu, 2016). Joints, which are vertical or near-vertical fractures in bedrock or regolith along which there has been little or no movement, are typically interpreted to form in response to compressive stress, although there are other possible causative factors (e.g. Olson and Pollard, 1989). Joints almost always develop in sets with three distinct orientations, two of which are at right angles to each other (e.g. Scheidegger, 2001). Joints in the Midcontinent have been shown to influence the orientations of both pre- and post-glacial drainages (Eyles et al., 1997).

The three-dimensional orientation of bedrock joints can be measured only in surface exposures or cores, however satellite imagery has been used to estimate the two-dimensional distribution of lineaments over relatively large areas (e.g. Cooley, 1983; Stix 1982; Suzen and Toprak, 1998). These lineaments may represent a variety of natural and anthropogenic features, and the assumption that they represent joints should be made with caution. Condra (1908) emphasized the porous nature of the Fort Hays Member in northeastern Nebraska and he also noted its prominent jointing. Cooley (1983) used Landsat imagery to map lineaments over an area that includes Cedar County, the results of which show three consistent orientations, two of which are at right angles to each other (Fig. 6). More research is necessary to confirm if these lineaments are joints, and if so, what effects they may have on the hydrogeology and bedrock topography of the area. Limestone commonly weathers along horizontal bedding planes, and assessing the intersection of joints and bedding planes is important to understanding the hydraulic characteristics of the formation.

The structure contour map of the top of the Niobrara Formation along the subcrop and outcrop belt (Fig. 7) was constructed from altitudes calculated using the geologic logs of more than 7,300 wells and test holes. The altitude of the top of the formation ranges from a high of about 2,350 ft (716 m) in Red Willow County on the eastern flank of the Cambridge arch, to a low of about 1,200 ft (366 m) in Knox County, within the Missouri River trench. In Red Willow and Furnas counties the contoured surface generally slopes downward to the east, reflecting the structure of the arch. In southern Harlan and Franklin counties the Niobrara Formation crops out along the Republican River (Miller et al., 1964; Dreeszen et al., 1973; Eversoll et al., 1988) and the effects of erosion are evident in the way the contours extend up the valleys (Fig. 7). In Webster County the surface of the Niobrara Formation undulates, forming two highs and two lows, which may impact groundwater flow in the overlying Quaternary deposits (Teeple et al., 2009). The bedrock high in northern Webster County extends eastward into Nuckolls County, where it underlies the divide between the Little Blue River and Republican rivers and hosts more than 110 wells that produce all or part of their water from the Niobrara Formation. Low areas in the Niobrara Formation occur to the north and northeast in Adams and Hamilton counties (Fig. 7) and are covered by as much as 300 to 350 ft (91 to 107 m) of Quaternary sediments, respectively. Along the subcrop belt north of the Platte River the top of the Niobrara Formation does not appear to undulate, probably due to post-Cretaceous erosion and deposition. At the northern end of the subcrop belt in Knox, Cedar, and Dixon counties, the elevation of the surface decreases northward. The estimated

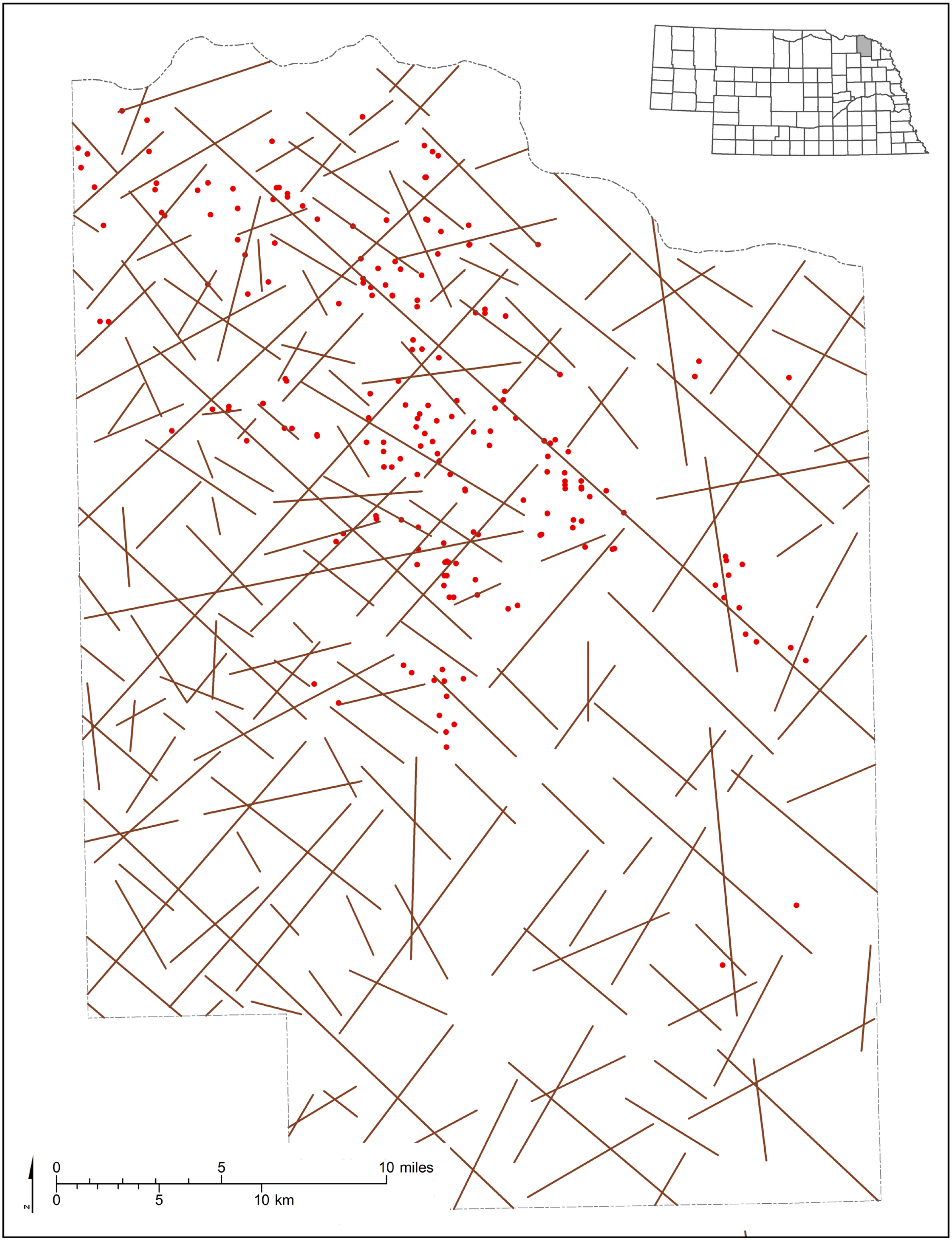


Figure 6. Lineaments in Cedar County as mapped by Cooley (1983).
Dots represent wells completed entirely in the Niobrara aquifer.

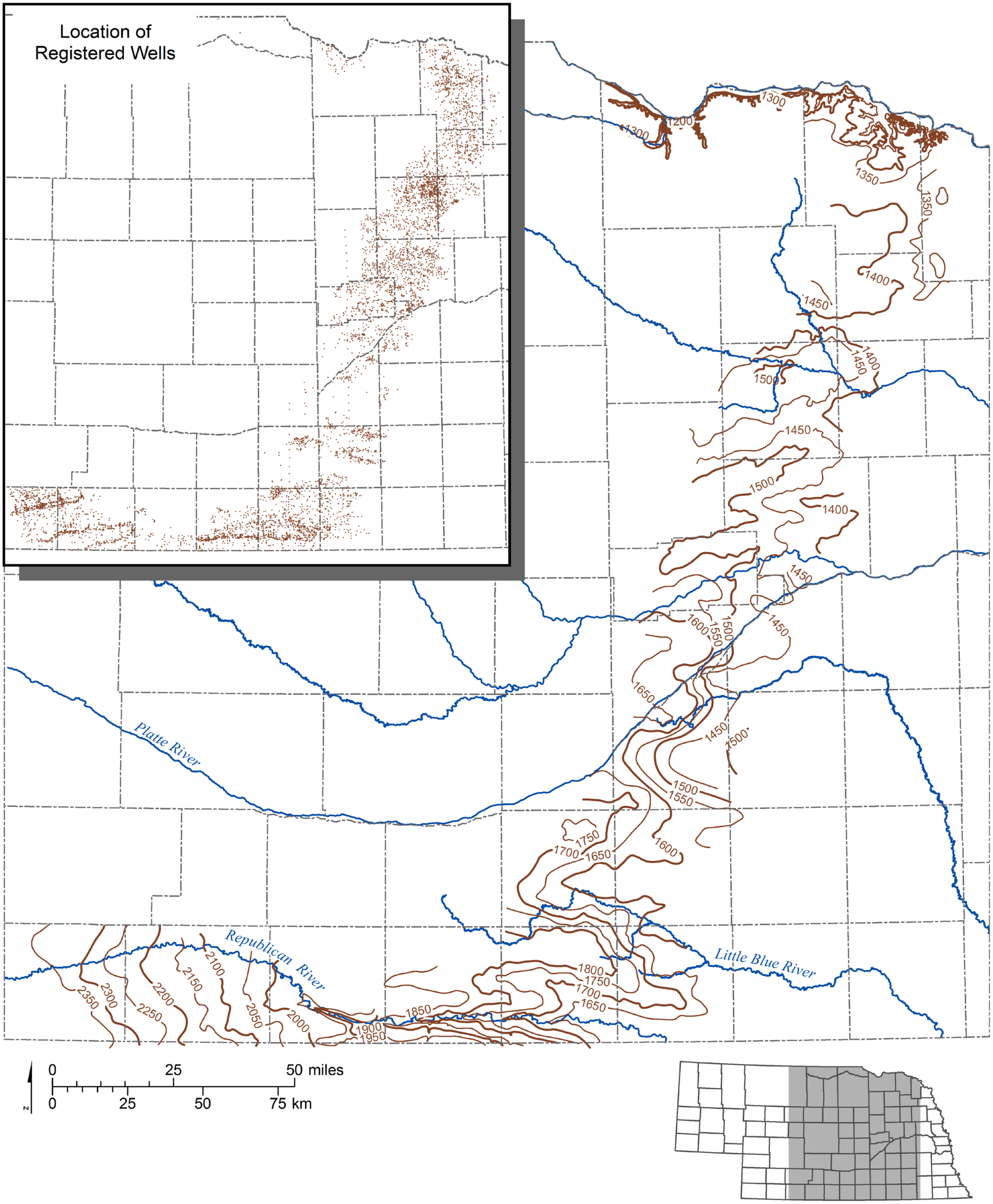


Figure 7. Structure contour map of the estimated top of the Niobrara Formation in feet above mean sea level. Dots on the inset map represent registered wells and test holes in which the top of the Niobrara Formation was identified. Contour interval is 50 feet.

elevation of the surface adjacent to the Missouri River in Nebraska is similar to maps produced for neighboring counties in South Dakota (Bugliosi, 1986; Jorgensen, 1971). East of the subcrop belt the Niobrara Formation has been completely eroded, and west of the subcrop belt it dips gently westward into the basin, where it is buried at progressively greater depths by the overlying Pierre Shale, Paleogene and Neogene sedimentary rocks, and Quaternary sediments (e.g. Witzke et al., 1983; Burchett, 1986).

The Niobrara Formation surface mapped in this publication (Fig. 7) generally corresponds to the bedrock surface mapped by previous authors (Burchett et al., 1988; McGuire and Peterson, 2008; Exploration Resources International, 2015a). The most significant difference between this map and its predecessors is in southern and western Dixon County, where approximately 30 registered well logs show yellowish chalk or "shale" recoded at the bottom of their logs (Nebraska Department of Natural Resources, undated). In the absence of any other data, these logs appear to indicate the eastward extension of the Niobrara Formation into that area, differing from the most recent bedrock map of Nebraska (Burchett, 1986), which shows no such extension. A second difference between figure 7 and previous maps is a possible bedrock high shown in northern Madison and northwestern Stanton counties, which is clear neither in Burchett et al. (1988) nor in McGuire and Peterson (2008), although it corresponds with results from airborne geophysical mapping (Exploration Resources International, 2015a).

Most of the wells used as data points in the present study area do not fully penetrate the Niobrara Formation, precluding the development of an isopach map. Previous studies and bore holes suggest the Niobrara Formation thickness in Knox County generally ranges from about 150 to 225 ft (46 to 69 m), but has been completely eroded in parts of the Missouri River trench (Divine et al., 2016). The maximum thickness of the Niobrara Formation in Cedar County is approximately 200 ft (61 m) (Nebraska Department of Natural Resources, undated), and similar values of the formation's thickness have been reported for adjacent southeastern South Dakota (Bolin, 1952; Christensen, 1974; Jorgensen, 1971; Bugliosi, 1986). In Nuckolls County the estimated maximum remaining thickness of the formation is approximately 100 ft (30 m), although petroleum bore holes to the west in Franklin County indicate the uneroded thickness of the Niobrara Formation there is at least 415 ft (126 m).

Nature of Porosity and Permeability

No comprehensive study of the porosity and permeability of the Niobrara Formation has been undertaken in Nebraska, especially with respect to hydrogeology, but speculations about the nature of both parameters may guide future work. Much of the porosity in the Niobrara aquifer *per se* is probably fracture porosity, but the porosity and permeability of the Niobrara Formation overall is complex—particularly when considered from the standpoint of petroleum production in areas west of the present study area. Michaels (2014) identified multiple types of submicroscopic (≤ 400 nm) pores in the Niobrara Formation in the Denver-Julesburg basin.

The porosity of precursor marine sediments may have been as great as 80%, but compaction by dewatering and grain reorientation and breakage at a microscopic scale, as well as any potential early cementation that may have occurred, reduced this value considerably during early burial, after which later-burial pressure dissolution and reprecipitation of calcium carbonate reduced it even more (e.g. Scholle, 1977b; Pollastro and Scholle, 1986). Burial depth and porosity exhibit a clear inverse relationship in chalks of the Niobrara Formation, the porosity decreasing to approximately 10% with deep burial (Lockridge and Scholle, 1978). Studies in Colorado oil producing areas have shown that the amount of fracturing and permeability in the Niobrara Formation is controlled by tectonic setting, lithology, and the crystal forms of calcite that are present (e.g. Vincelette and Foster, 1992; Pollastro, 1992).

The porosity of constituent chalks is probably much higher than 10%, perhaps in excess of 40%, in areas under which the Niobrara Formation was buried at shallow depths, such as central to eastern Nebraska, although permeability would likely be approximately 10 millidarcies (mD) or less

(Lockridge and Scholle, 1978). It is possible that other types of secondary porosity besides fracture porosity—including porosity conferred by local dissolution of chalky limestone—may contribute to the aquifer properties of the formation. In parts of Kansas, sand and gravel in both fractures and "solution zones" are said to be the source of groundwater in the Niobrara Formation (Macfarlane, 2000).

Given the shallow burial depths of the Niobrara aquifer in eastern Nebraska, the lithology and amount of weathering at the top of the formation are probably important variables affecting the usefulness of the formation as an aquifer. In Cedar County, limestone and chalk are logged at the top of the formation almost as often as shale, and there are more than 30 references to lost circulation in the well logs, which typically indicates that the bore hole has intercepted a fracture or extensive bedding planes. In some cases, lost circulation occurred in chalk or limestone, but in many instances it was noted in units logged as shale, which suggests weathering is an important factor in aquifer yield.

HYDROGEOLOGY OF THE NIOBRARA AQUIFER IN NEBRASKA

Hydrogeologic Framework

Cenozoic sediments and sedimentary rocks, where present, constitute the primary aquifer in the vicinity of the Niobrara subcrop and outcrop belt (e.g. Summerside et al., 2005; Exploration Resources International, 2015a, b). The thickness of these sediments varies from zero to more than 350 ft (107 m). Transmissivity of the principal aquifer varies from less than 20,000 gallons per day per foot (28.8 cm^2/s) across much of the subcrop and outcrop belt north of the Platte River, to more than 200,000 gallons per day per foot (288 cm^2/s) in areas south of the river (Summerside et al., 2005; Divine, 2014; 2015). The highly variable nature of the principal aquifer is due to a variety of factors including Plio-Pleistocene paleovalleys that were eroded into the bedrock surface, variable depositional environments for the Neogene sediments, and glaciation in the northeastern part of the study area (e.g. Condra and Reed, 1959; Souders, 1976; Divine, 2015; Korus et al., 2016).

There are no documented springs issuing from the Niobrara aquifer within Nebraska, but there are seeps, and possibly springs, at outcrops of the Niobrara Formation along the Missouri River bluffs, which also occur along the bluffs on the South Dakota side of the river (Jorgensen, 1971; Bugliosi, 1986). R.F. Diffendal, Jr. (personal communication, 2017) noted that the U.S. Army Corps of Engineers struggled to seal a Niobrara Formation fracture emitting pressurized water during construction of the Harlan County dam in southern Nebraska. In southwestern Kansas, Latta (1944) documented seven springs emanating from the Fort Hays Limestone along the Pawnee River in Finney County. The openings of the fracture springs were sheet-like and the source of the water was the overlying Ogallala Group. The discharge of the springs varied from less than one gallon per minute to about 4 gpm (15 lpm).

Well Locations and Yield

According to registered well logs (Nebraska Department of Natural Resources, undated) there are currently about 230 active registered wells screened entirely in the Niobrara Formation in Nebraska (Fig. 8). These wells are located mostly where the Niobrara Formation is relatively shallow. In all but nine of the wells, the top of the Niobrara Formation is less than 100 ft (30m) below land surface, with the greatest depth at about 180 ft (55 m). Test hole drilling in South Dakota also found that the highest yielding areas of the aquifer occur where the top of the Niobrara Formation is less than 100 ft (30 m) below ground surface (Jorgensen, 1971).

There are three distinct clusters of wells in the Niobrara aquifer in or near Cedar, Madison, and Nuckolls counties (Fig. 8). Cedar County has some 200 registered active wells that produce

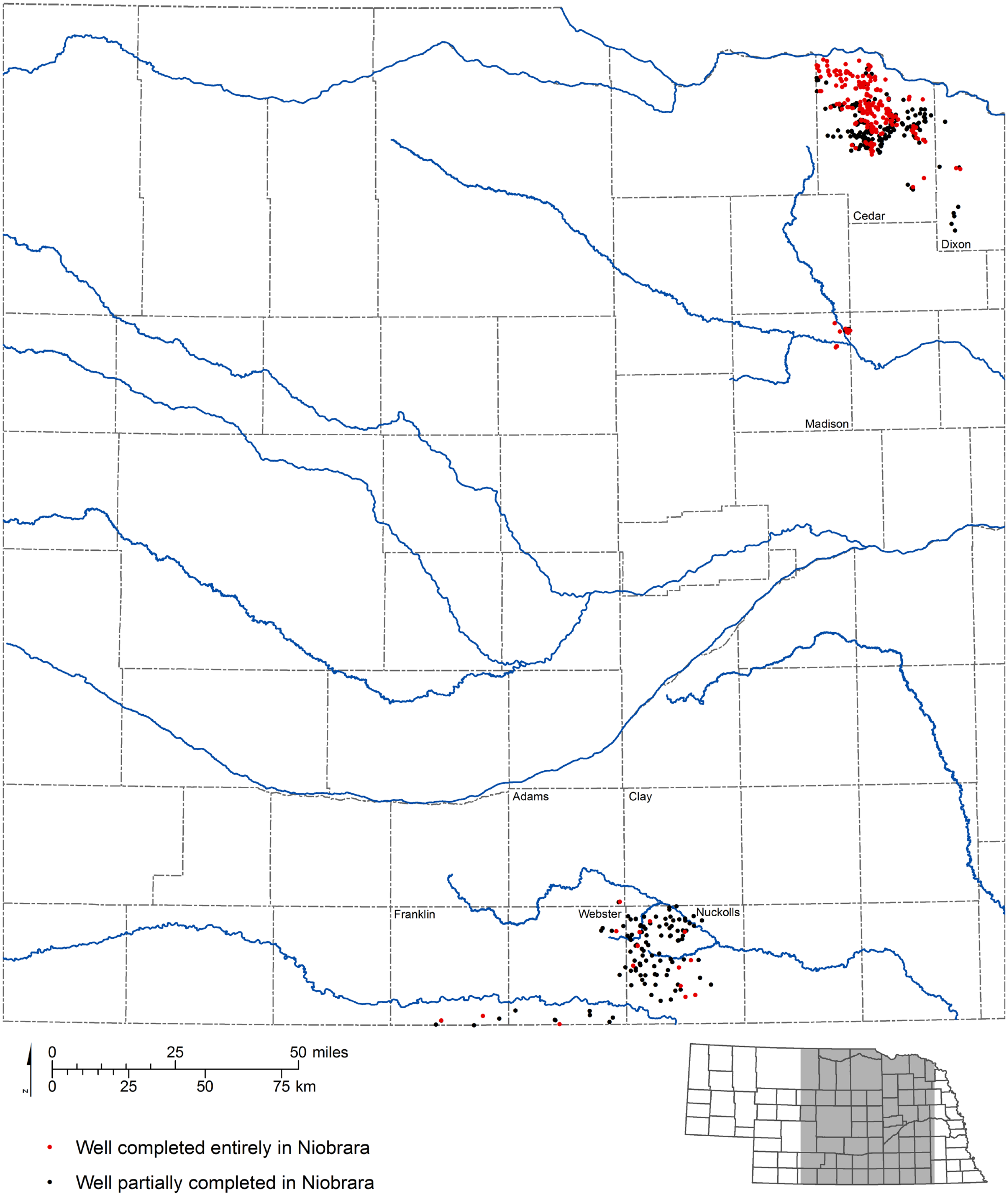


Figure 8. Locations of Niobrara wells. Red dots represent wells completed entirely in the Niobrara aquifer, black dots represent wells partially completed in the aquifer.

exclusively from the Niobrara aquifer. About 44 of these wells are irrigation wells that produce over 500 gpm (1,893 lpm), and the average yield for all exclusively Niobrara irrigation wells in the county is 430 gpm (1,628 lpm). The City of Hartington also has a Niobrara well that is registered as producing 550 gpm (2,082 lpm). These high-yielding wells are generally located near Bow Creek, Norwegian Bow Creek, and West Bow Creek where the overlying Cenozoic deposits are thin or absent.

Wells sourced entirely from the Niobrara Formation in Cedar County are statistically shallower than all active wells in the county grouped together (Fig. 9), based on the Mann-Whitney rank-sum method to test significance. The median Niobrara well depth is 100 ft (30 m) compared to 130 ft (40 m) for all active wells in Cedar County. Niobrara wells are probably more common at shallower depths because the Niobrara aquifer is used where Quaternary and Paleogene sediments are thin or absent and the Niobrara Formation more extensively weathered.

The Madison County cluster of wells includes 15 wells that produce exclusively from the Niobrara Formation (Fig. 8). These wells are mostly domestic or monitoring wells, but there is one commercial well registered as producing 225 gpm (852 lpm). The static water level in these wells is at or above the top of the Niobrara Formation, and the domestic wells yield on average about 20 gpm (76 lpm). Ten additional wells in the area are partially sourced from the Niobrara Formation. Geologically, the wells in this cluster are located where the North Fork of the Elkhorn River and the Elkhorn River cross a Niobrara Formation bedrock high.

In and around Nuckolls County, there are 16 wells screened entirely in the Niobrara aquifer, mostly located on the upland divide between the Little Blue and Republican rivers, but a few are located south of the Republican River near the Kansas border (Fig. 8). The Niobrara aquifer wells in and around Nuckolls County are used for both domestic and livestock purposes, yield about 10 gpm (38 lpm) on average, and indicate a mix of confined and unconfined conditions, with the confined wells located in northwestern Nuckolls County and Adams County. An additional 110 wells are partially screened in the aquifer, although many of these wells extend only into the weathered shale or chalky shale that is common at the top of the Niobrara Formation in south-central Nebraska.

Water Level Elevations

Figure 10 shows a static water-level elevation map in the Niobrara Formation in Cedar County produced from water-level information collected in any month between 1997 and 2015 from about 165 wells screened entirely in the Niobrara aquifer. The contours should be interpreted as average conditions during the 18 years the data represents. The highest water-level elevation measured at a well is approximately 1,480 ft (427 m), but the highest contour drawn is 1,400 ft (427 m) because data is insufficient to draw contours in the southern part of the county where hydraulic heads are highest. The lowest water-level elevation is approximately 1,220 ft (378 m). The groundwater gradient is generally north-northeast toward the Missouri River. Two groundwater divides, which correspond to highs on the bedrock surface, are evident: one between Antelope Creek and Second Bow Creek, and another between West Bow Creek and Bow Creek (Fig. 10). There may also be a small groundwater divide between West Bow Creek and Second Bow Creek. Groundwater flow in adjacent parts of South Dakota is generally south toward the Missouri River (Jorgensen, 1971; Bugliosi, 1986).

Water-level contours “V”-upstream on the middle reaches of Bow Creek and West Bow Creek (Fig. 10), suggesting that these creeks gain groundwater, at least in some reaches. Geologic cross sections and airborne geophysical surveys confirm that these creeks could be hydrologically connected to groundwater, even though there may be a thin remnant of Pierre Shale between the alluvium and the Niobrara Formation (Hanson and Dillon, 2012; Exploration Resources International, 2015b). Norwegian Bow Creek has a thicker sequence of Pierre Shale separating the alluvium and Niobrara Formation (Exploration Resources International, 2015b) and may not be hydrologically connected to groundwater. There are no supporting cross sections through Beaver

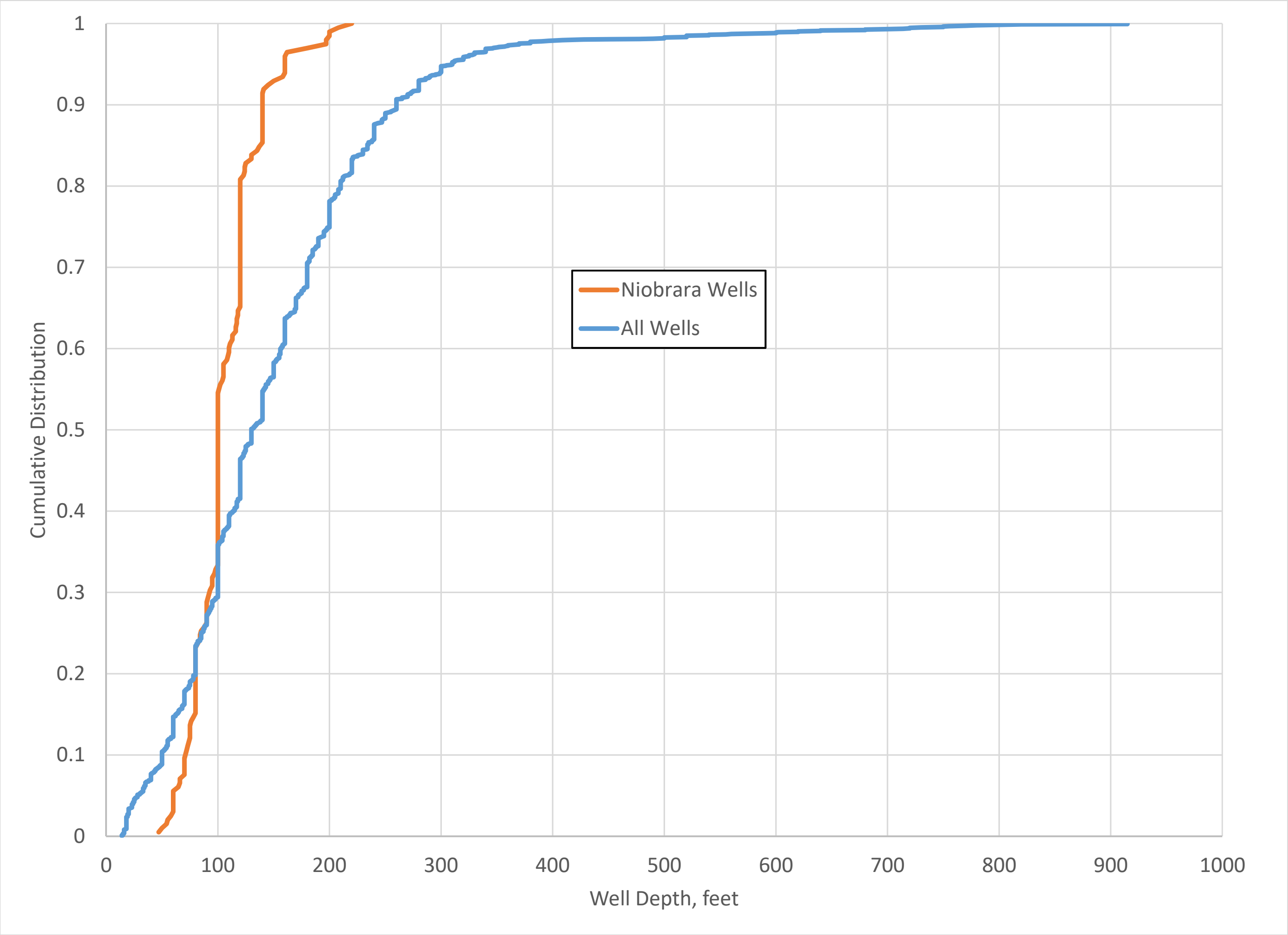


Figure 9. Cumulative distribution function of well depth in Cedar County. Blue line represents all active wells in the county, the orange line represents only wells completed entirely in the Niobrara aquifer. The median well depth corresponds to the depth where the line crosses 0.5 on the y-axis. Medians of the two groups are statistically different (Mann-Whitney, p < 0.001).

Creek and Antelope Creek in northwestern Cedar County, but the water-level contours suggest that Beaver Creek may be gaining groundwater.

The Niobrara aquifer is unconfined in some places and confined in others. Most of the Niobrara wells in Cedar County are unconfined, but 30 wells have static water levels measured at least 10 feet above the top of the Niobrara Formation since 1997. Wells in fractured bedrock may exhibit confined conditions when they intercept and source water from horizontal bedding planes (Walker, 1956). If the bedding planes that supply water to the well are connected laterally to groundwater where the water table is at a higher elevation than the bedding planes, the water level in the well will rise above the top of the bedrock (Walker, 1956). In Cedar County, confined conditions occur mostly in the southern part of the aquifer, although some confined wells are scattered among unconfined wells elsewhere in the county. The confined wells indicate the presence of a low-permeability unit thick enough to limit vertical recharge from precipitation. In these confined wells, horizontal flow is probably the dominant source of recharge. The unconfined wells in this setting may be shallower than the confined wells or be hydraulically connected to joints. In adjacent counties in South Dakota, the Niobrara aquifer is also mostly unconfined, with some localized confining conditions (Jorgensen, 1971; Bugliosi, 1986).

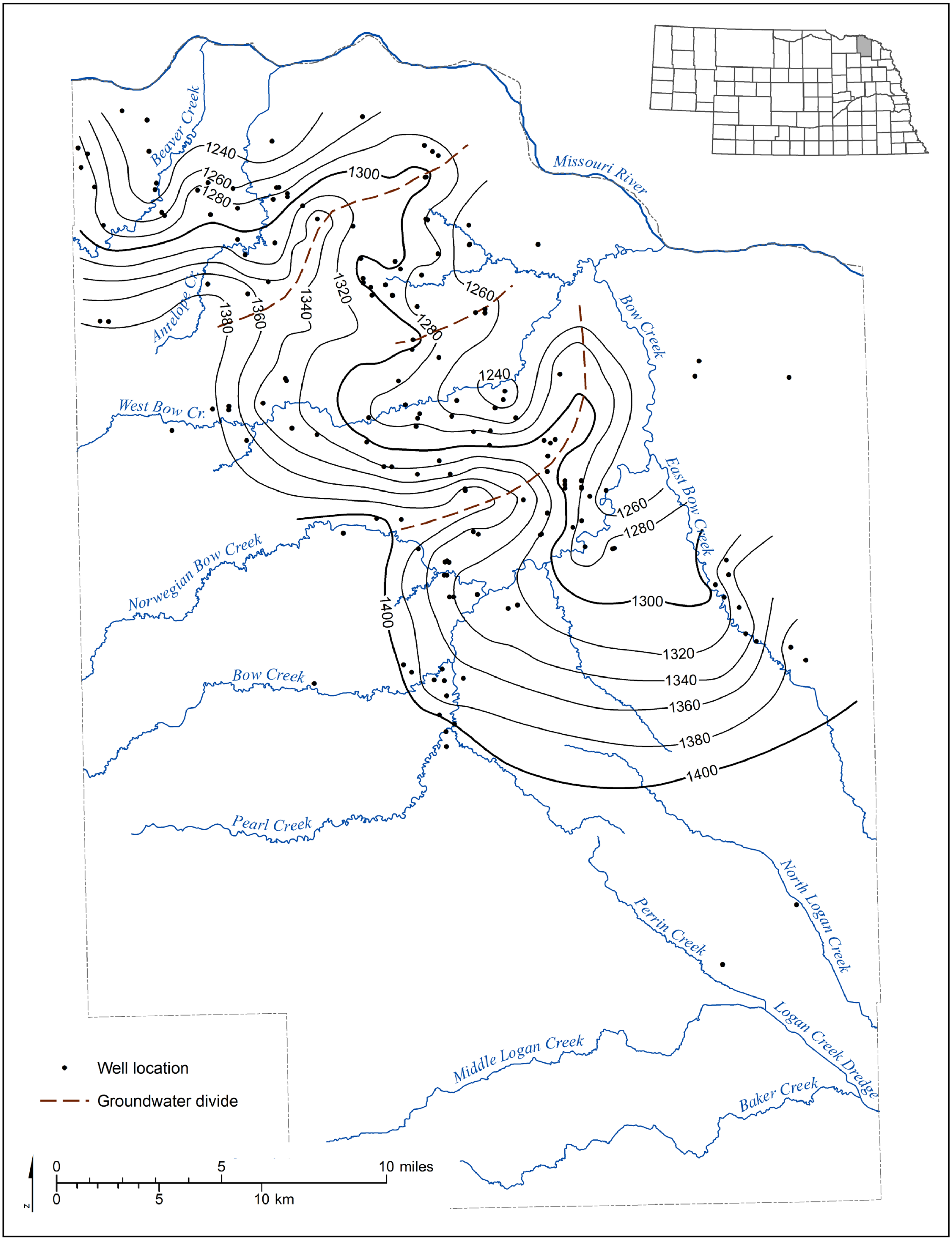


Figure 10. Estimated static water level in the Niobrara aquifer in Cedar County. Dots represent registered wells from which the initial static water level measurement was used. Contour interval is 20 feet.

In Madison County, static water elevations in the Niobrara aquifer are higher than in Cedar County, ranging from about 1,500 to 1,520 ft (457 to 463 m), and wells appear to have a static water level at or above the top of the formation. The static water level in Nuckolls County is even higher at 1,615 to 1,845 ft (492 to 562 m). Confined conditions are present in the northwestern part of Nuckolls County, and unconfined conditions in the southern part of the county and extreme southern Webster and Franklin counties.

Water Quality

Comparison of water quality results suggest that the water quality of the Niobrara aquifer varies within and between states (Table 1 and Fig. 11). The water quality in the Niobrara aquifer is generally good, although sulfate, hardness, and total dissolved solids become elevated in the northern part of the study area. Iron (Fe) and/or manganese (Mn) concentrations are also at or above the recommended limits at various places across the subcrop and outcrop belt. The high sulfate (SO_4^{2-}) content may produce an undesirable rotten egg odor and black tint to the water when it is initially pumped from the well. This black color disappears fairly quickly, but may leave a black precipitate (microscopic sulfide particles), and the water is corrosive to pump rods and pipes (Kume, 1977). Weathering of pyrite (FeS_2), an iron sulfide mineral, produces an acid solution enriched in iron (Fe^{2+}) and sulfate (SO_4^{2-}) (Gosselin et al., 2001), which is the probable source of iron and sulfate in the Niobrara aquifer. Elevated sulfate concentrations have also been documented in the Codell aquifer in Boyd and Knox counties (Divine et al., 2016).

Calcium is the dominant cation in all of the water samples collected in Nebraska for this study, with the exception of one well in the northwestern corner of Cedar County where sodium is the dominant cation. In the historic South Dakota water samples, the dominant cation was either calcium or sodium, but Yankton County has a significant magnesium concentration. The Yankton County results also included elevated iron and manganese, with some nitrate. Selenium is not

Parameters (mg/L)	Recom-mended Limits	Nuckolls County, NE	Madison County, NE	Cedar County, NE	Yakton County, SD	Bon Homme County, SD
Well Depth (ft)	--	147	96	109	--	--
Year of Collection	--	2017	2017	2017	~1980	~1970
Number of Samples	--	5	4	7	8	11-26
Bicarbonate	--	274	205	252	380	289
Boron	7	0.01	0.08	0.23	0.66	1.7
Calcium	--	92	90	191	320	241
Chloride	250	26	21	18	36	53
Fluoride	2	--	--	--	1	--
Hardness	--	276	292	635	1160	827
Iron	0.3	0.3	0.12	0.7	4.2	--
Magnesium	--	11	16	39	290	55
Manganese	0.05	0	0.17	0.09	0.53	--
Nitrate	10	5.1	3.9	4.6	6.4	--
pH	6.5-8.5	7.25	8.06	7.41	--	--
Potassium	--	4	7	11	17	26
Sodium	30-60	23	15	45	79	209
Sodium Adsorption Ratio	3	0.6	0.4	1.0	1	3.8
Specific Conductance (micro-mhos)	--	657	657	1241	2140	2160
Sulfate	250	15	89	457	960	891
Total Dissolved Solids	500	427	427	807	1750	1860

Table 1. Average concentrations of water quality parameters collected from the Niobrara aquifer in Nebraska and South Dakota.

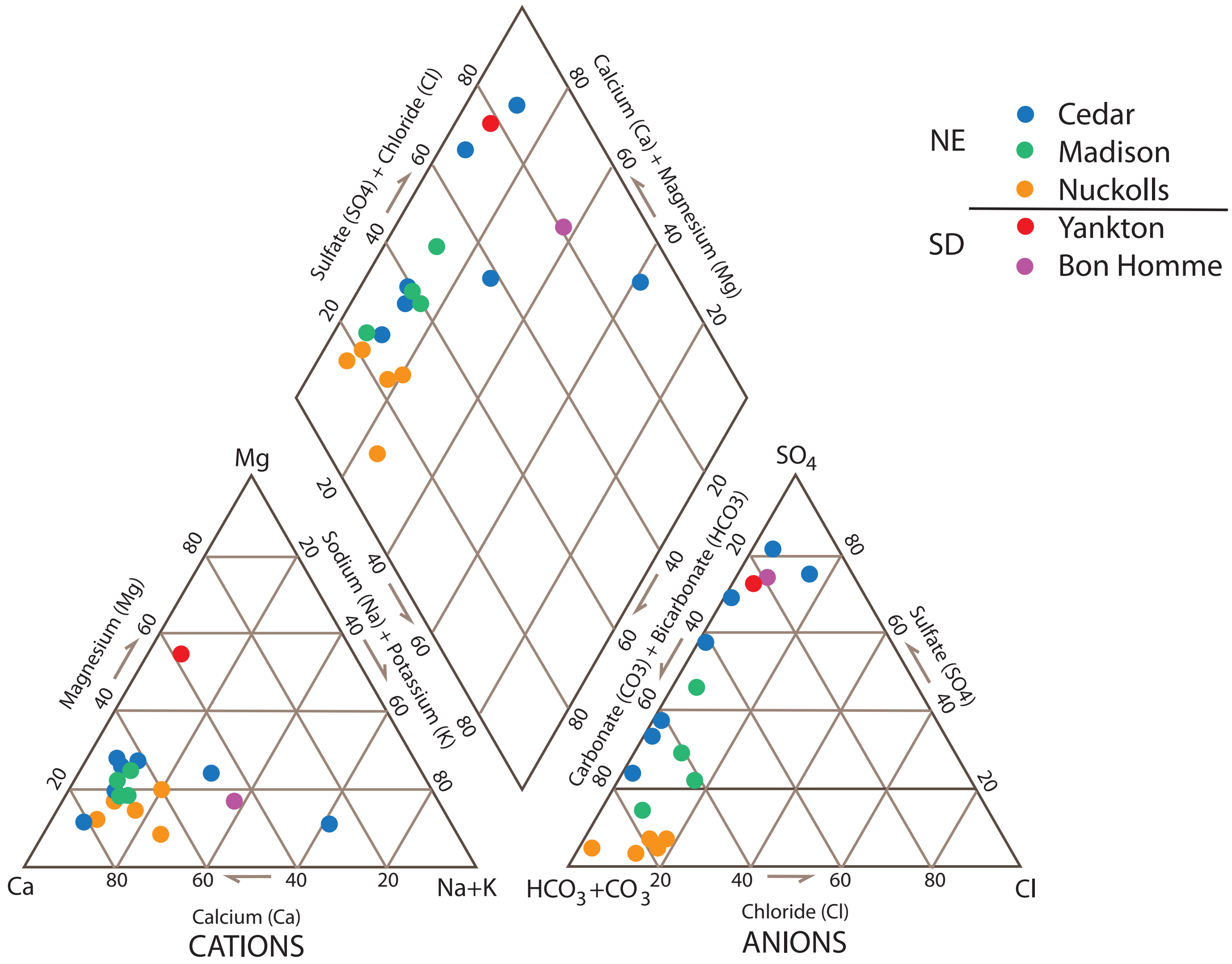


Figure 11. Piper diagram depicting major ion water chemistry collected in 2017 from individual wells in Nebraska. Data from South Dakota are county averages of historic samples.

shown in Table 1, but it is a potentially toxic element that has complex chemical speciation and is widely associated with the Niobrara Formation and Pierre Shale (Kulp and Pratt, 2004). Previous research (Jorgensen, 1971) in Bon Homme County, South Dakota determined that selenium might be elevated in Niobrara wells there.

Recharge and Discharge

The Niobrara Formation is mapped as bedrock over a large area (Fig. 7), therefore, there are a number of probable sources of recharge to the Niobrara aquifer. Where the formation is shallow and unconfined, infiltration of precipitation is likely an important source of recharge (Engberg and Druliner, 1987). Precipitation may infiltrate through overlying sediments, but would probably infiltrate faster along joints, if present. Where the formation is deeper and the wells are confined, the source of recharge is probably groundwater movement into the formation from adjacent geologic units.

Water conserves its elevation energy when it recharges to a confined aquifer, so the pressure heads measured in confined wells are similar to the altitude of the recharge area if pumping has not significantly reduced the pressure in the aquifer. The pressure heads in wells in southern Cedar County are between 1,400 and 1,480 ft (427 to 451 m), so one way to identify potential recharge areas is to look for locations where the top of the Niobrara Formation is at that elevation. If a location with matching elevation is identified, the second step is to verify the aquifer could readily receive recharge from surface water or precipitation at that location. In southern Cedar County there is an area in the vicinity of Perrin and Middle Logan creeks (Fig. 10) where the top of the Niobrara is at about the right elevation and it could receive recharge, but more research is needed to confirm if it is indeed a recharge area.

In Madison County west of Norfolk, the Elkhorn River and Battle Creek cross a Niobrara bedrock high with an elevation of about 1,500 ft (457 m), an elevation similar to the hydraulic heads in the Niobrara wells in the vicinity of Norfolk. Historic CSD test holes show saturated sand and gravel directly overlying the Niobrara Formation here, preliminarily suggesting it as a possible recharge location because water would easily pass through the highly permeable sand and gravel, however further study is necessary.

The most likely recharge area for the confined Niobrara wells in northwestern Nuckolls County and Adams County may be Ogallala Group sediment that covers a high on the Niobrara Formation at about 1,800 ft (549 m) in the vicinity of Blue Hill, Nebraska. However, this conclusion is speculative and based only on the general permeability of Ogallala Group sediments, regional groundwater flow direction, and similarity in altitude and pressure head. The assessment of recharge across the Niobrara aquifer clearly requires additional research.

Groundwater from the Niobrara aquifer naturally discharges to some of the creeks in Cedar County, as evidenced by the static water-level contours that bend upstream around the creeks (Fig. 10). Data are insufficient to draw static water-level contours in the Niobrara Formation in and around Madison and Nuckolls counties, and natural discharge locations are therefore difficult to identify. Pumping wells that produce water from the aquifer are, however, a form of artificial discharge.

SUMMARY

The Niobrara aquifer in eastern Nebraska, characterized here for the first time, is an important local resource because it supplies all of the water to about 230 active registered wells and some of the water to an additional 320 wells. These wells are located in three discrete clusters in or around Cedar, Madison, and Nuckolls counties. Four hundred of these wells are located in and around Cedar County, including about ten wells in Dixon County. The median depth of Niobrara wells in Cedar County is 100 feet (30 m). The groundwater gradient in the Niobrara aquifer in Cedar County is generally toward the Missouri River, although reaches of Bow Creek, West Bow Creek, and Beaver Creek may gain flow from the aquifer and locally affect the gradient. Most of these wells are in an unconfined hydraulic setting, except for about 30 wells in which the static water levels indicate confining conditions. This variation may be caused by localized lithology, well depth, and potential hydraulic connection with joints.

Less is known about the Niobrara aquifer in Madison and Nuckolls counties and adjacent areas because the number of Niobrara wells there is much smaller. On the basis of static water levels in the wells, however, possible recharge areas may be located in the vicinity of Battle Creek and Blue Hill, respectively. Field investigations and additional data will be needed before any additional analysis of recharge areas can be made.

The aquifer is probably recharged by vertical infiltration through overlying sediments (and possibly along joints), and with horizontal recharge along bedding planes. Water quality in the aquifer is generally potable, although iron, manganese, and sulfate concentrations sometimes exceed the recommended maximum contaminant levels. Sulfate concentrations tend to be especially high in the northern part of the study area, probably due to the weathering of pyrite, an iron sulfide mineral that is naturally common to the area.

DIRECTIONS FOR FUTURE WORK

Features that may affect permeability within the Niobrara Formation include: joints, solution enlarged joints/faults, solution cavities, bedding planes, or rubble zones, all of which are largely uncharacterized in Nebraska. Future data collection in the Niobrara aquifer should include lineament mapping and identification of joints and faults to further study the potential relationship between wells, streams, and geologic structure in Cretaceous bedrock. Wireline coring might confirm the presence of joints and outcrop studies could define joint orientations. Coring could also verify how groundwater is stored and transmitted in the aquifer.

The potential hydraulic connections between the Niobrara aquifer and surface water should also be verified through monitoring water levels and quality in nested monitoring wells (one well is screened in alluvium and the other screened in the Niobrara aquifer) and analyzing the resulting data. The same data should be compared to stream-gauge and stream-water quality data in the study area. Lewis & Clark Natural Resources District recently installed nested wells along Bow Creek and West Bow Creek in Cedar County, along with pressure transducers to record water level data. Water quality is routinely sampled in these wells. Bow Creek is currently gauged and that effort should continue. The same approach of using nested wells and stream gauges to investigate hydraulic connection could be employed in Nuckolls County in the vicinity of Elk Creek and/or Liberty Creek (Fig. 1).

Finally, recharge zones should also be identified, which may be accomplished with airborne electromagnetic surveys flown in grids to map permeable geologic material in three dimensions and age dating of groundwater along the potential recharge flow path. Results from further research could lead to more successful and cheaper siting of Niobrara wells and contribute information relevant to management strategies.

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A normal fault in the Niobrara Formation, probably related to Laramide deformation. Arrows indicate direction of movement. Scale at bottom right is 6.5 ft (2 m). Outcrop is located near Bloomington, in Franklin County, Nebraska.

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